Insulation Thermal Coefficient Measurement in Distribution Transformer under Unbalanced Operation

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***Abstract-T*ransformers play a key role in power distribution networks. A reliable and endless supply of electricity is highly dependent on good operation of these elements. A huge number of customers are directly supplied via any of the transformers. Loading of the transformers under unbalance conditions is an important factor that influences the life of their insulation. In this paper we will consider two typical 315 KVA, 20 kV distribution transformers with the same characteristics but under different operating conditions. One transformer supplies a three phase industrial load while another transformer supplies an urban area consisting variety of three and single phase loads and experiences unbalance conditions that highly influence its insulation system. Thermal coefficients and remnant life of two distribution transformers are measured and show a remarkable difference between thermal coefficients of two transformers.**

Keywords- Insulation; Thermal coefficient; Distribution transformer; Unbalanced operation; Life assessment

I. INTRODUCTION

Transformers play a key role in power distribution networks. Studies show, life of a transformer is equal to its insulation life which depends on mechanical and electrical reliability [1-3]. Stresses like mechanical, electrical and thermal affect oil-paper insulation system of the transformers [4]. The main factors that determine the insulation life of oil-immersed liquid-cooled transformers are the transformer load, ambient temperature, moisture content and oxygen content in oil [5]. Transformer's insulation system can degrade to the point that they can't withstand sever events such as lightning strikes or short circuits that occur on the network. Transformers that are operated under unbalanced conditions will suffer more extreme stresses than those operated under balanced conditions. This undesired status highly affects the insulation system of the transformer and reduces its life time. Relaxation phenomena in insulations and solid dielectrics were reported by several researchers. Polarization and depolarization current measurements of aged transformers are investigated in [6]. Temperature effects on transformer oil-paper insulation system are presented in [7]. Modeling transformers with internal incipient faults and an equivalent circuit of transformers insulation are proposed in [8], [9].

The oil-paper insulation is commonly used in the distribution transformers. Oil plays a fundamental role to maintain required insulating level and also protects windings against over heating. When a distribution transformer is asymmetrically loaded, thermal and mechanical stresses are increased, insulation system damages and oil is also polarized [6, 7]. The chemical and physical deteriorations are induced by these stresses. In this paper we will experiment and analyze two typical 315 KVA, 20 kV distribution transformers with the same characteristics. Transformers have the same installation date. Transformer 21D180 supplies a 3 phase industrial load while 21A060OF supplies an urban area consisting variety of three and single phase loads via a low voltage distribution network. Thus 21A060OF experiences unbalance conditions that highly influence its insulation system.

II. THERMAL AGEING FORMULATIONS

A distribution transformer, from the electrostatics points of view, may be modeled with a capacitance between the various conducting parts or between conducting parts and the tank. This capacitance is highly dependent on insulation type and the oil inside the tank [8, 9]. Transformer life is directly proportional to its insulation life. Insulation life time in the transformers is influenced by several factors. Load and ambient temperature are the most important factors. Ageing degradation is accelerated under unbalance conditions and high ambient temperature. Dielectric conductivity is a measure of performance of dielectric as an insulator. The higher electrical conductivity, σ, causes the higher thermal losses (heating) for a given field, so in this condition decreases the critical breakdown voltage. Several models have been introduced to assess life estimation of insulation in the transformers [1-4, 10, 11]. We use thermal ageing to estimate transformers remaining life. In this case, the temperature dependence of a solid dielectric specific conductivity has the form [4, 10]:

$$\sigma = \sigma_0 \cdot e^{\beta \cdot \Delta\theta} \tag{1}$$

Where σ is the specific conductivity in a unit volume for temperature rise above the ambient temperature ($\theta_{ambient}$=20 °C), σ_0 is the initial specific conductivity, β is the thermal coefficient of insulating material and **Δθ** is the temperature rise in °C above the ambient temperature. The Δθ is estimated from equation (1):

$$\Delta\theta = \frac{\ln \frac{\sigma}{\sigma_0}}{\beta} \tag{2}$$

Equation (2) can be used to determine transformers remaining life time .This equation can be rewritten in the following form:

$$\beta = \frac{\ln \frac{R_0}{R}}{\Delta\theta} \tag{3}$$

R0 is initial resistance of the transformer and R is measured resistance value at the temperature rise $\Delta\theta$. The thermal coefficient β can only be calculated if resistance of the insulation is known in two different temperatures.

III. DATA AND DESCRIPTIONS

In this section two similar 20kV distribution transformers are considered and their thermal coefficients are measured. Table I shows characteristics of both transformers. The only difference between them is about their loading status. The oil/paper is the common insulation system used for both transformers and the natural circulation of oil and air (ONAN) is the common cooling method.

TableI SPECIFICATIONS OF TYPICAL TRANSFORMERS

Specifications	**Transformer ID**	
	21A060OF	***21D180***
	315	315
Primary voltage (kV)	20	20
Secondary voltage(kV)	0.4	0.4
Uk%	4.7	4.7
Load PF	0.92	0.82
Cooling system	ONAN	ONAN
Installation date	2000	2000

The three phase loading status of transformer 21A060OF is shown in Fig.1. Operation under such unbalance conditions will significantly increases the thermal and the mechanical stresses on oil/paper insulation. The neutral wire carries a significant current. It mainly affects the transformer insulation system, but also will displace its neutral point. Fig.2 shows a daily loading of transformer 21D180. We were interested in examining both transformers to find the behavior of their insulation systems under their operational conditions. Our experiments are generally related to the oil/paper insulation.

IV. OIL EXPERIMENT

The breakdown voltage (VB) characteristic is the most important factor that determines the quality and lifetime of the oil used in the distribution transformers [12]. The higher breakdown voltage causes the higher insulating resistance. The higher resistance results in a better thermal coefficient β which means the better quality and lower thermal losses of insulation system. Table II depicts the experimental results of breakdown voltage of two transformers. We have performed the tests for five times to achieve more accurate results and the mean value has been intended as breakdown voltage (VB). The results show that the oil of 21D180 transformer has higher breakdown voltage than oil of 21A060OF transformer.

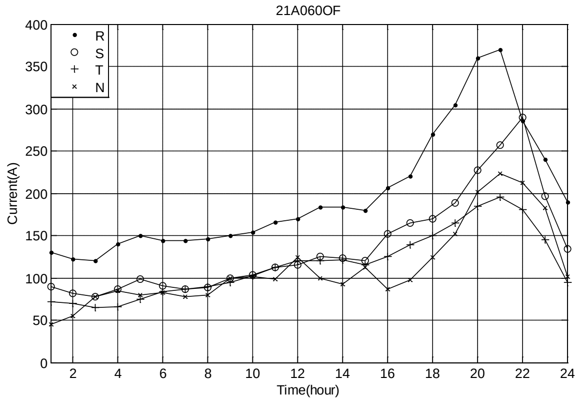

Fig.1 Daily loading status of transformer 21A060OF

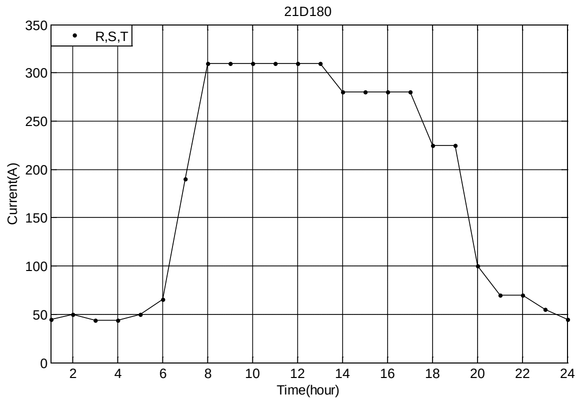

Fig.2 Daily loading status of transformer 21D180

TableII THE OIL BREAKDOWN VOLTAGE TEST

Test number	**21A060OF**	**21D180**
	V_B(kV)	***V_B(kV)***
1st	35.7	44.3
2nd	41.4	52.7
3rd	38.7	45.2
4th	29.3	50.4
5th	40.7	57.3
average	37.16	49.98

V. INSULATION RESISTANCE MEASUREMENT

Our main purpose is to calculate the insulation thermal coefficients of both transformers. To achieve this goal, the insulating resistances between high voltage winding and Tank (R1) and high voltage to low voltage windings (R2) are required. The time dependent insulating resistance measured at ambient temperature is shown in Fig.3. The optimum time to measure insulating resistance is 10 min. The insulating resistances measured at 10 min for different temperatures are shown in Table III. The higher value for R2 than R1 is due to the solid insulation between high voltage and low voltage windings of the transformers. It may be observed that from Table III, the insulating resistance of the transformer 21D180

has higher value than 21A060OF. This means that the insulating system of transformer 21D180 has better quality than the insulating system of transformer 21A060OF. We will describe in next section, this will result better thermal coefficient (β) that insures insulating system remaining life time. The insulating resistance is a function of temperature [7]. The higher temperature makes the lower insulating resistances. This inverse relation is due to the oil ionization in higher temperatures.

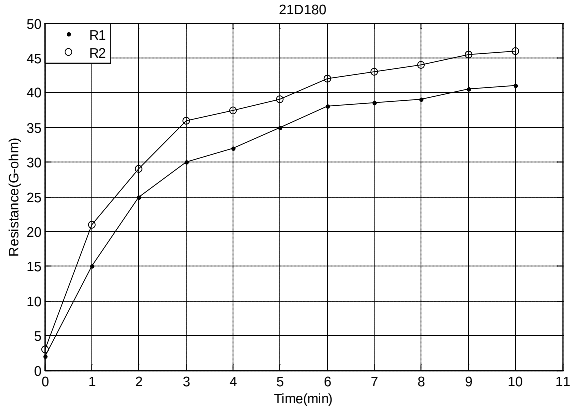

Fig.3The measured resistances R_1 and R_2 at ambient temperature (function of time) for transformer 21D180

TableIII MEASUREMENT OF INSULATING RESISTANCES (10 MIN)

21D180 (315KVA)			**21A060OF (315KVA)**		
Temperature (°C)	***R₁(GΩ)***	***R₂(GΩ)***	***Temperature (°C)***	***R₁(GΩ)***	***R₂(GΩ)***
20	41	46	20	27	34
32	18	19.5	32	14	16
45	9	10.5	45	7.1	8.7
60	6	6.4	60	4	4.2
75	3.2	3.7	75	2.6	2.8

VI. THERMAL COEFFICIENT MEASUREMENT

The thermal coefficient β is an important factor that determines quality of the transformer insulation system. The calculated thermal coefficients corresponding to various temperature rises are shown in Table IV. The higher values of β1 and β2 of the transformer 21D180 represent better quality of its insulating material. The thermal coefficients of both transformers are functions of temperature rise.

TableIV THE CALCULATED THERMAL COEFFICIENTS β_1 AND β_2

21D180			**21A060OF**		
$\Delta\theta$	β_1	β_2	$\Delta\theta$	β_1	β_2
12	0.0686	0.0715	12	0.0547	0.0628
25	0.0606	0.0590	25	0.0534	0.0545
40	0.0480	0.0438	40	0.0477	0.0522
55	0.0463	0.0458	55	0.0422	0.0453

VII. TRANSFORMER LIFE ASSESSMENT

Transformer life time is equal to its insulation life [13-15]. The thermal coefficient β is an insulating characteristic and describe insulation quality. If transformer insulation thermal coefficient is known at two different temperatures, by measurements, the change of its insulating resistance R_0 (at ambient temperature) during its life in the network is earn from equation (3). The other required parameter is R to obtain Δθ from equation (3). The following typical mathematical expressions are used to calculate transformers remaining life in days, months and years:

Remaining life time in days:

$$t = 264.29728\times10^5 \times e^{-0.0879\Delta\theta} \tag{4}$$

Remaining life time in months:

$$t = 3.96329\times10^5 \times e^{-0.0819\Delta\theta} \tag{5}$$

Remaining life time in years:

$$t = 1.57945\times10^5 \times e^{-0.0938\Delta\theta} \tag{6}$$

First we use the relation (6) to find the range of the remaining life and then the proper relation (5) or (4) for a closer estimation of the remaining life. The calculated transformers remaining life times are shown in Table V. In Table V, β_1 and β_2 are the calculated thermal coefficients of the insulation, R_0 is the measured insulating resistance of the transformer at ambient temperature, R = 20 MΩ is the theoretical minimum allowed insulating resistance of the transformer and **Δθ** is the equivalent temperature rise, calculated by the equation (3).

TableV TRANSFORMERS LIFE ASSESSMENT

Transformer ID	**21D180**	**21A060OF**
β_1	0.0686	0.0547
β_2	0.0715	0.0628
R_{10}(GΩ)	41	27
R_{20}(GΩ)	46	34
R(MΩ)	20	20
$\Delta\theta_1$ (°C)	111.16	131.77
$\Delta\theta_2$ (°C)	108.26	118.45
Remnant life 1(months)	44	8
Remnant life 2(months)	56	24

VIII. CONCLUSION

Insulating systems are the most important parts of the distribution transformers. The good operation of these elements ensures long life time and low heating losses for the transformers. Under operating conditions, insulating systems experience variety of stresses like thermal, mechanical and electrical. Load and ambient temperature are the most critical causes accelerating these stresses on insulating systems. In this paper, we examined two typical 315 KVA, 20 kV distribution transformers with the same characteristics but under different

operating conditions. One transformer supplies a balanced industrial load while the other one is a public transformer that supplies an unbalanced urban load. Our experiments depict that the oil breakdown voltage (VB) of balanced transformer is 34.5 percent higher than unbalanced transformer and there is also a remarkable difference between thermal coefficients of both transformers. This means that the balanced transformer has the higher oil and solid insulation remnant life. The oil and solid insulating remnant life of the balanced transformer are 5.5 and 2.33 times more than the unbalanced transformer respectively.

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